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Investigation of failures in Irish Raised Bogs

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ABSTRACT

This paper presents the results of field geophysical testing and laboratory testing of peat from Carn Park and Roosky raised bogs in the Irish Midlands. The motivation for the work was highlight the importance of these areas and to begin to attempt to understand the reasons for the failure of the bogs despite them having surface slopes of some 1°. It was found that the peat is typical of that of Irish raised bogs being up to 8 m thick towards the "high" dome of the bogs. The peat is characterised by low density, high water content, high organic content, low undrained shear strength and high compressibility. The peat is also relatively permeable at in situ stress. Geophysical ERT and GPR data shows a clear thinning of the peat in the area of the failures corresponding to a reduction in volume from dewatering by edge drains / peat harvesting. This finding is supported by detailed water content measurements. It was also shown that the peat base topography is relatively flat and indicates that the observed surface movement has come from within the peat rather than from the material below the peat. Potential causes of the failures include conventional slope instability, the effect of seepage forces or the release of built up gas in the peat mass. Further measurements are required in order to study these in more detail.

Key words: peat; translational (planar); geophysics; resistivity, ground penetrating radar; Ireland;

INTRODUCTION

Landslides in blanket bogs in Irish upland areas have been relatively well studied (Creighton, 2006; Dykes and Kirk, 2001; Long and Jennings, 2006; Long et al., 2011) and their causal factors are well known (Boylan et al., 2008; Warburton et al., 2004). However, failures have also occurred in raised bogs in the Irish Midlands which have very shallow slopes. Raised bogs are a rare habitat in the European Union (EU) and as such have been listed as priority areas under Annex I of the E.U. Habitats Directive (European-Union, 1992). Ireland has a high proportion of the total EU resource of raised bogs (over 50%) and therefore developing an understanding of the reasons for these failures is of significant importance.

In order to investigate the causes of these events two such failures at Carn Park bog, near Athlone, Co. Westmeath and at Aghnamona bog, near Roosky, Co. Leitrim have been studied. This paper presents the results of investigations at these sites, which included field geophysical and laboratory geotechnical testing of the peat. The main objective of this work is to raise awareness of the importance of these areas so future damage can be minimised.

RAISED BOGS

According to Creighton (2006) a raised bog is "an accumulation of peat with its greatest thickness being at the centre giving it a convex upward surface". Raised bogs were formed, over post glacial lakes, which occupied a large part of the Irish midlands in the immediate post glacial period, some 9,000 years before present. Lake bed soils, such as calcareous marls (Long and Rogers, 1995), initially accumulated. Then vegetation began to encroach from the margins of the lakes towards the center, leaving an accumulation of organic matter. Subsequently as the lake was gradually filled in, fen peat, which was fed by mineral-rich groundwater, began to accumulate in drier conditions about 7,000 years ago. Fen peat then began to use up the available nutrient reserve and less nutrient-hungry soils began to form. By now the original basin was completely peat filled. The material towards the upper surface was woody in nature and its upper limit was determined by the water table.

About 2500 years ago the climate became much wetter. Further growth of raised bogs was then totally dependent on the influence of rainwater and generally comprised the development of sphagnum mosses. The raised bog grows when the sphagnum at the surface die. At the surface the actively growing sphagnum develops outwards in the form of a spreading mat. This upper active layer is typically 0.2 m to 0.5 m thick. Ultimately raised bogs in Ireland tend to be 3 m to 12 m thick with an average of about 7 m (Feehan and O'Donovan, 1996).

HISTORICAL FAILURES ON RAISED BOGS

The Geological Survey of Ireland (GSI) holds a database of all known landslide events in Ireland (www.gsi.ie). Fourteen failures on raised bogs are recorded and most of the GSI data comes from the work of Feehan and O'Donovan (1996). These are noted to have occurred throughout the year whereas failures on upland blanket bogs mostly occurred in the wetter autumn and winter months. All except one of the events listed occurred before 1900 and hence due to the lack of information the cause of the failures are not well known. Feehan and O'Donovan (1996) suggest the two main causal factors are the build up of water and gas pressures within the bog or the creation of near vertical faces on the bogs due to turf cutting for domestic fuel consumption.

For example, the failure of Kapanihane bog in County Limerick in 1697 was attributed to the accumulation of water either at the base of the bog or in the middle of peat "sandwich" following a period of heavy rainfall. This caused the bog to swell up and eventually burst. Several other failures are similarly described as "bursts", "explosions" or "eruptions".

The failure of Woodfield bog, near Kilmaleady, County Offaly in 1821 was precipitated by the lateral movement of highly decomposed peat from the base of a steep bank. The summer of 1821 was exceptionally dry and it allowed the local turf-cutters to excavate peat to a greater depth than was usual. Some 9 m high faces existed prior to the failure which left in its wake a valley 9m deep, 2.5 km long and about 0.5 km wide.

SITE LOCATIONS AND GENERAL DESCRIPTION OF FAILURES

Carn Park

Carn Park bog is situated 8 km east of Athlone, Co. Westmeath in the Irish midlands, see Figure 1. The site is a candidate Special Area of Conservation (cSAC) for raised bogs as listed in Annex I of the E.U. Habitats Directive. Due to its ecological importance it was selected for restoration as part of Coillte's E.U. "LIFE" funded project entitled "Demonstrating Best Practice in Raised Bog Restoration in Ireland". A survey of the site prior to restoration in 2003 (Conaghan, 2003) showed much of the bog had been planted with conifer trees up to 25 years old. Aerial photographs taken pre-restoration in 1995 and 2000 showed no evidence of failure in the southern area of the bog adjacent to a plantation. However some small failed areas were evident in the northern part of the bog, see Figure 2. These were adjacent to some vertical faces which had been created by turf cutting for fuel. The failures manifested themselves as a series of concentric vertical cracks, approximately 100 m in diameter, radiating back from the face.

Similarly aerial photographs from 2003 showed no evidence of cracking in the southern area. This failure was first noticed on a site visit by the E.U. LIFE project steering group in September 2006 and was later shown to be present in photographs from 2005 which were taken prior to restoration, see Figure 3a. The southern failure also occurred just behind an area where peat was being harvested for domestic purposes. Another important feature of this area is a drain which runs approximately east west just south of the failed area. Again, the failure comprised a series of concentric cracks radiating from the southern edge of the bog. At that time it was estimated that the failed area extended over a width of some 250 m and extended 400 m into the bog (Derwin, 2006). The zone of cracking appears to be confined to the east by the main forestry drain. Originally the northern limit of the cracking coincided with a town-land boundary drain.

Restoration of the site took place in 2005 and comprised removing the plantation and blocking the drain network (Derwin, 2008). Subsequent aerial photographs of the area from 2007, 2009, 2010 and 2011 (see Figure 3b) show no change in the lateral extent of the failed area but some small growth in the area of the cracking towards the former northern extent of the forestry.

Some photographs of the cracks in the southern area are shown on Figure 4. Figure 4a shows a newly formed pool at the south-west corner of the cracking from 2006. The flora present in the pool suggests it was newly formed at that time. It was thought to be the origin of the cracking and occurs at the top of an old peat-cutting drain. There was an obvious bulge in the face bank where the peat has slid southwards. A photograph of some of the cracks, taken in February 2011, is shown on Figure 4b. It can be seen that they are up to 1 m wide and are of significant depth.

Roosky

Aghnamona Bog is classified as a National Heritage Area (NHA) and is situated 2 km east of the village of Roosky. It is located some 45 km north of Carn Park, see Figure 1. A view of the area in 2005, before the failure, is shown on Figure 5a. The Roosky Bypass (N4 Primary Road) was constructed between July 2006 and December 2007. The main impact of the works on Aghnamona Bog involved cuts of up to 5 m to facilitate the construction of two link roads and a large roundabout on the south west corner of the bog as well as some realignment and deepening of the surface drains by up to 1.5 m (MEL, 2004). The failure was first noticed in 2008, after completion of the road works, and the nature of the failure is illustrated on Figure 5b. Similar to Carn Park it has manifested itself as a series of concentric cracks, about 70 m in diameter, radiating about 100 m into the bog away from the roadway / drainage works associated with the roundabout on the Roosky Bypass. Some photographs of the cracks are shown on Figure 6. It can be seen that they are up to 1 m wide and are of significant depth.

PREVIOUS MONITORING AT CARN PARK

A series of 10 timber stakes were installed in October 2006 across cracks at Carn Park to enable monitoring of the crack movement and to mark the extent of the failed area. These stakes were resurveyed in August 2008 and showed additional movements of up to 0.2 m between the stakes.

In May 2005 a series of standpipes were installed to record any changes in water level due to bog restoration activities, e.g. drain blocking or tree removal. Initially water levels were found to be up to 0.6 m below the surface of the mature conifer plantations and close to the surface of the open bog. With the removal of the conifers (Summer 2005) and the blocking of drains (Summer 2006), there was a significant rise in the water level. Extensive areas of open water were created in the open bog and the water level was found to remain close to the bog surface throughout most of the year. This is a crucial requirement for bog restoration.

FIELD TESTING

A series of peat sampling and geophysical testing exercises were carried out at both bogs. At Carn Park, peat probing and ground penetrating radar (GPR) and electrical resistivity tomography (ERT) was carried out on 17th and 18th October 2011. Subsequently block sampling of the peat was carried out on the southern failed area on 9/11/11 and on the northern failed area on 5/2/12. At Roosky, peat probing, block sampling and a similar set of geophysical tests were carried out on 9th and 10th June 2011. Details of these testing exercises are as follows.

Peat probing and sampling

The peat probing was carried out using a “Russian” sampler, which produces a 0.5 m long, hemispherical core of the peat. The depth limit with the particular probes used at these sites was 4.1 m. At Carn Park one peat probe to 3.0 m was carried out at the junction of the two ERT lines, see Figure 3b. Penetration beyond 3.0 m was not possible due to resistance from roots and wood fragments. Small (≈50g) samples were taken from the Russian sampler for laboratory water content determination. Additional samples were taken by the Russian sampler along the line of ERT profile R2 at depths of 1.0 m and 1.5 m. Block samples (≈ 200 mm x 200 mm x 50 mm high) were also extracted by hand from the walls of the cut face at both the southern and northern failed areas.

At Roosky two peat probes, including sampling, to the full depth of the equipment were carried out at the eastern extremity of the failed area and in the centre of the failed area, see Figure 7. Additional samples were taken with the Russian sampler along the line of ERT profile R2 at depths of 0.5 m and 1.5 m. Block samples (≈ 200 mm x 100 mm x 50 mm high) were also extracted by hand from the walls of the drains located along the western boundary of the failed area.

Electrical resistivity tomography (ERT)

Two-dimensional (2D) electrical resistivity tomography (ERT) surveys were performed at both sites as shown on Figures 3b and 7 respectively. Data was acquired using a multi-electrode Campus Tigre resistivity meter with a 32 takeout multicore cable and 32 conventional stainless steel electrodes. An electrode spacing of 2 m was chosen in order to provide an adequate trade-off between depth and resolution. A four electrode Wenner array configuration was used to acquire multiple readings for each 2D ERT profile. The Wenner array was used here as it generally provides a good signal to noise ratio.

Data processing was carried out using the software Res2Dinv. This software uses a forward modelling subroutine to calculate the apparent resistivity values, and a non-linear least-squares optimisation technique is used for the inversion routine following the procedures of Loke and Barker (1996). All inversions performed converged to root mean square (RMS) errors of less than 6% within 5 iterations and the final RMS errors were usually about 1.5%.

Ground penetrating radar (GPR)

The GPR work was carried out using a 100 MHz antenna with a 0.2 m trace interval. The GPR is linked to an accurate RTK dGPS (Global Positioning System) which enables rapid coverage, spatial relocation to GPS co-ordinates as well as providing topographic information. Further details can be found, for example, in Trafford (2009), where it was shown that GPR has proved to be the most effective geophysical technique for accurate assessment of peat thickness. At Carn Park data were collected from across, as well as around the perimeter of the failure, in order to assess the distribution of peat throughout the survey area.

For the Roosky site the GPR lines are shown on Figure 7. At both sites, the GPR equipment was man hauled across the bog surface as shown on Figure 8.

LABORATORY TESTING

Oedometer tests

Conventional maintained load oedometer tests were carried out according to BSI (1990). Generally the initial load was 5 kPa and the load increment ratio was 2.0. Each increment was maintained for 24 hours. A slightly larger sample than normal (37.5 mm high as opposed to the standard 19 mm) was used in order to try to capture the mass behaviour of the naturally variable fibrous peat. The specimen diameter was 76 mm.

Direct simple shear tests (DSS)

For the DSS tests, a Geonor H12 Direct Simple Shear apparatus was used. Bjerrum and Landva (1966) provide a full description of the apparatus. Undrained tests are conducted as constant volume tests where the height of the specimen is held constant throughout the shearing stage of the test. Test specimens have a diameter of 79.5 mm and a height of 19 mm. In general the test procedures adopted were those typically used at the Norwegian Geotechnical Institute (NGI) as reported by Andresen et al. (1979). Samples were consolidated in a single step to the estimated in situ effective stress (σ_{v0}') of 10 kPa and was left to consolidate overnight. On the following day, samples were sheared at a constant linear displacement which gave a shear strain rate of approximately 4% shear strain per hour. The undrained shear strength (s_u) is taken to be equal to either the peak horizontal shear stress ($\tau_{h\text{-}max}$) attained during shearing or alternatively the shear stress measured at 15% shear strain, whichever occurs first.

Von Post classification

The peat material has been classified according to the scheme described originally by von Post and Granlund (1926) as extended by Hobbs (1986).

Loss on ignition

Loss on ignition testing was carried out by igniting approximately 10g peat samples in a muffle furnace at 440 °C for 5 hours, Arman (1971). The resulting value is often considered to be equivalent to the organic content of the peat.

RESULTS

Peat thickness and surface morphology

The main objective of the GPR work was to profile the sub peat base and to relate this to the surface topography. Trafford (2009) details this process for a large area of Bord na Móna (Irish Peat Board) bogs in the Irish Midlands. The GPR trace can also show some others structures within the peat mass, which may correspond to changes in degree of humification, pockets of coarse fibres or wood fragments. At Carn Park data were collected from across the southern failed are as well as around its perimeter in order to assess the distribution of peat across the survey area. It appears the base of peat is relatively flat at about +56 mOD (see also Figure 10a). The surface topography shows peat surface level to vary between +58 mOD and +62 mOD with the lowest point at the edge of the cut to the south west of the survey area. The slope of the bog surface behind the southern failed area is about 0.7°. Overall Peat thickness was found to vary from approximately 2.5 m to 8 m.

Similarly for the Roosky site the base of the peat was shown to be relatively flat, with a base elevation between +40 mOD and +41 mOD (see also Figure 10b). The surface topography shows a pronounced lower level area, near to +44.5 mOD, in the failed zone. Behind the failed area the surface of the bog rises gradually to an elevation of +48 mOD at a slope of about 1°. These two sets of data can be combined to produce the plot of peat thickness shown on Figure 9a and the 3D plot of surface and peat base topography on Figure 9b. Peat thickness varies between about 4 m close to the edge of the bog and 7 m towards the centre.

For both sites the GPR data shows a clear thinning / reduction in volume of the peat in the area of the failures. In both cases the peat base topography is relatively flat and does not follow the much more pronounced variation in topography mapped at the surface. This suggests that the observed surface movement has come from within the peat rather than from the underlying material.

In addition to indicating peat thickness, the ERT data also provides data on the underlying materials. Figures 10a and 10b show the ERT profiles running perpendicular to the failures for both Carn Park and Roosky respectively. The relatively flat peat base profile is clear for both sites. For Carn Park the peat appears to be underlain by low resistivity material which is consistent with the presence of limestone till indicated on the GSI soils maps (www.gsi.ie). Argillaceous limestone bedrock is also resolved below the till again as expected from the geological maps of the area. At Roosky, beneath the peat is a till mostly derived from sandstone bedrock which in turn overlies Waulsortian reef limestone, as expected from the geological records.

For both sites, the resistivity is seen to increase with distance into the bog. This finding will be explored in conjunction with a study of the water content of the peat below.

Description and classification of peat

A comparison of the von Post and Granlund (1926) log of peat probes P1 from both sites (see Figures 3b and 7) is shown on Figure 11. At both sites, from an engineering point of view, the peat can be described as a relatively uniform very soft light brown fibrous peat (BSI, 2002). The Roosky peat appears to be slightly more decomposed with H = 6 near the surface compared to H = 4 for Carn Park. At both sites the degree of decomposition decreases slightly with depth. The Carn Park peat has a greater portion of fine fibres and wood fragments but the coarse fibre content is greater for Roosky.

Basic index data

A summary of water content, bulk density and loss on ignition values against depth for both sites are given on Figure 12. In general the water content of the Roosky peat is greater than that of Carn Park, corresponding to the greater degree of decomposition of the Roosky peat. At Carn Park water content decreases from about 1200% at 0.5 m towards 750% at 3 m. There is no difference between values taken from the southern and northern failed areas. For Roosky the values are relatively constant, with an average of about 1250%. For both sites the majority of the data correspond to tests taken near the failure edge or scarp. It can be seen that tests from Probes P1 at both sites show higher water contents than the rest of the data. These probes were located away from the failed face. This finding is explored in more detail below.

For both sites bulk density values are similar and average about 1.05 Mg/m^3, which is typical for Irish peat (Hanrahan, 1954). Loss on ignition values are high and are on average about 98%, confirming the almost complete organic nature of the material.

A series of additional samples were taken using the Russian sampler, within the failure zone, running perpendicular to the face along the line of ERT profile R2 at both sites. These samples were taken at depths of approximately 1.0 m and 1.5 m at Carn Park and at 0.75 m and 1.5 m at Roosky, see Figure 13a and 13b respectively. It is clear there is a very significant reduction in water content of the peat toward the face of the failure for both sites and for both test depths. At Carn Park the reduction in water content towards the face is more significant than that at Roosky due to the older age of the failure. The greater degree of drainage and consolidation that has occurred has meant that the water content values do not become uniform until about 100 m from the face. At Roosky the reduction in water content towards the face is clear but less substantial and values appear to become uniform about 50 m from the front edge of the failure.

It is clear from Figure 13 that the peat in the failed area has been drained and suffered a reduction in water content. This reduction in water content has led to loss of volume and resulted in surface settlement of the peat and is consistent with the findings of the GPR and ERT surveys described above.

Resistivity and water content

Following the inversion of the ERT data the modelled Roosky resistivity values at 0.5 m and 1.55 m depth were exported for the full length of the profile, see Figure 14. Although the exact depth of the exported data was not the same as that for the samples collected for water content analysis (0.75 m and 1.5 m), the observed trends are clear and a relationship between water content and resistivity is apparent. A reduction in resistivity was observed towards the edge of the failure, relating to a reduction in measured water content.

Previous laboratory studies, e.g. by Ponziani et al. (2011), show that the conductivity of peat shows a different dependence on water content above or below a pore fluid conductivity equal to that of the solid phase of the peat. The relationship observed in the Roosky and Carn Park sites indicates that the pore fluid conductivity is less than the solid phase and by draining the peat the reduction in water content would result in an increase in the bulk conductivity of the peat.

The relationship between water content and resistivity may, following further work, provide an innovative way in which to monitor the relative fluctuations in water content of organic soils without the need for in situ sampling and subsequent laboratory testing. This approach would be very useful where continued access to sensitive sites is not possible.

Compression and consolidation parameters

A summary of oedometer tests carried out on three samples from the southern failure area at Carn Park is given on Figure 15. The specimens, which were 37.5 mm high, were all obtained from the same block and were cut so that consolidation was in (i) the vertical plane, (ii) horizontal plane perpendicular to the cracks and (iii) horizontal plane parallel to the cracks respectively. All three specimens show similar highly compressible consolidation behavior as exhibited on the classical log σ_v' versus stain plot (Figure 15a). A feature of the behaviour is the relatively high permeability measured at or around in situ vertical effective stress (σ_{v0}') and then the significant reduction in permeability observed with increasing stress. There is no clear anisotropy of permeability evident in the test results.

Undrained shear strength of peat

DSS test results are summarised on Figure 16. Results are presented in the form of undrained shear strength (s_u) versus depth and normalised undrained shear strength (s_u/σ_v') versus depth. It can be seen that the results are similar for both sites with s_u increasing from about 6 kPa at the surface to 10 kPa for the deepest samples tested. The normalised s_u/σ_v' values for Roosky and Carn Park south show a gradual reduction from about 0.8 at the surface to 0.4 with depth. An s_u/σ_v' value of 0.4 is consistent with the strength of peat in the normally consolidated condition as was shown by Carlsten (2000) for Swedish peat and Boylan and Long (2013) for Irish peat from both blanket and raised bogs. The normally consolidated state of the Carn Park south peat below about 1.5 m is consistent with the data for the oedometer tests at 1.8 m shown on Figure 15. The peat at Carn Park north seems to be overconsolidated throughout its depth. This is likely to be due to the older age of the failure here and the greater amount of drainage and consolidation that has taken place.

STABILITY ANALYSES

Although a detailed stability analysis is beyond the scope of this paper, three possible failure mechanisms could be considered to explain the observed phenomena as follows:

- conventional slope failure due to applied shear stress exceeding the shear strength of the soils in the slope,
- failure due to water seepage,
- failure due to the influence of gas pressure.

Conventional slope stability analysis

In these analyses the disturbing force due to the weight of the soil mass are compared to the resistance provided by the shear strength of the soils in the slope using the principle of limit equilibrium. Given the very low slopes involved and the relatively high shear strength of the peat, it would be expected that high factors of safety would be calculated for such a conventional slope failure.

Seepage analysis

The observed water flow at the face of the failed areas together with the measured reduction in the water content of the peat towards the face suggests that seepage is occurring from the main body of the raised bog towards the edge. It is possible then that the seepage forces exerted by the flowing water are the cause of the observed cracks.

The failures observed at Carn Park and Roosky are very similar in nature to those reported by Landva (1980) and Landva (2007) for the instability of some peat cliffs in Escuminac peat at Miramichi Bay in New Brunswick, Canada. Similar to the observations at Carn Park and Roosky cracks were found to form a concentric semicircular pattern and existed at a distance of up to 40 m from the cliff face with the largest semicircles approaching 100 m in diameter.

A detailed analysis of the seepage forces on the peat mass would require some data on the tensile strength of the peat and on the variation in piezometeric pressure in the peat across the bog.

Failure due to gas pressure

Feehan and O'Donovan (1996) suggest that the gas emanating from peat is largely nitrogen (54% or so), methane (about 43%) with some some carbon dioxide (3%). A pale light is often seen to hover over bogs and this has been attributed to the spontaneous combustion of escaping methane. As detailed above there have been several failure of raised bogs in Ireland which have been attributed to "bursts" due to the build-up of water and gas pressures. However the nature of these failures is very different to those observed here. Feehan and O'Donovan (1996) refer to one case of a bog being "torn up and scattered as if by an explosion". Nonetheless some measurements of the build-up of gas pressure in the peat would be required in order to examine this mode of failure in more detail.

CONCLUSIONS

The purpose and motivation of this work was to highlight the importance of raised bogs and to explore the nature and thickness of the peat in order to attempt to understand the failures observed at the relatively flat Roosky and Carn Park sites. The following points can be concluded from this work:

1. Testing confirmed that the peat is typical of Irish raised bogs, to be up to 8 m thick and to be characterised by very high water content, low density, low undrained shear strength and high compressibility. The peat has relatively high permeability under in situ stress conditions.
2. Drainage along the edge of both bogs has caused dewatering of the peat. This has manifested itself in a reduced water content of the peat towards the edge of the failure zone and clear thinning and compression of the peat which has led to

surface settlement of the bog. The degree of consolidation is greater for Carn Park compared to Roosky because of the age of the failure.

3. Geophysical surveys (GPR and ERT) have shown that the peat base is relatively flat and does not follow the pronounced variation in surface topography. This suggests that the observed surface movement has come from within the peat rather from the material below the peat.
4. The relationship between water content and resistivity may provide an innovative way in which to monitor the relative fluctuations in water content of peat soils on sensitive sites where access is not readily available.
5. Any examination of the cause of failure should involve a fully coupled soil / water gas analysis. Further measurements, for example of the piezometeric and gas pressures in the peat, would be required in order to verify the actual cause of failure.

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FIGURES

Figure 1. Site locations

Figure 2. Section of 2005 aerial photograph of Carn Park bog showing northern failed area (courtesy Charise Mc Keown - Geological Survey of Ireland)

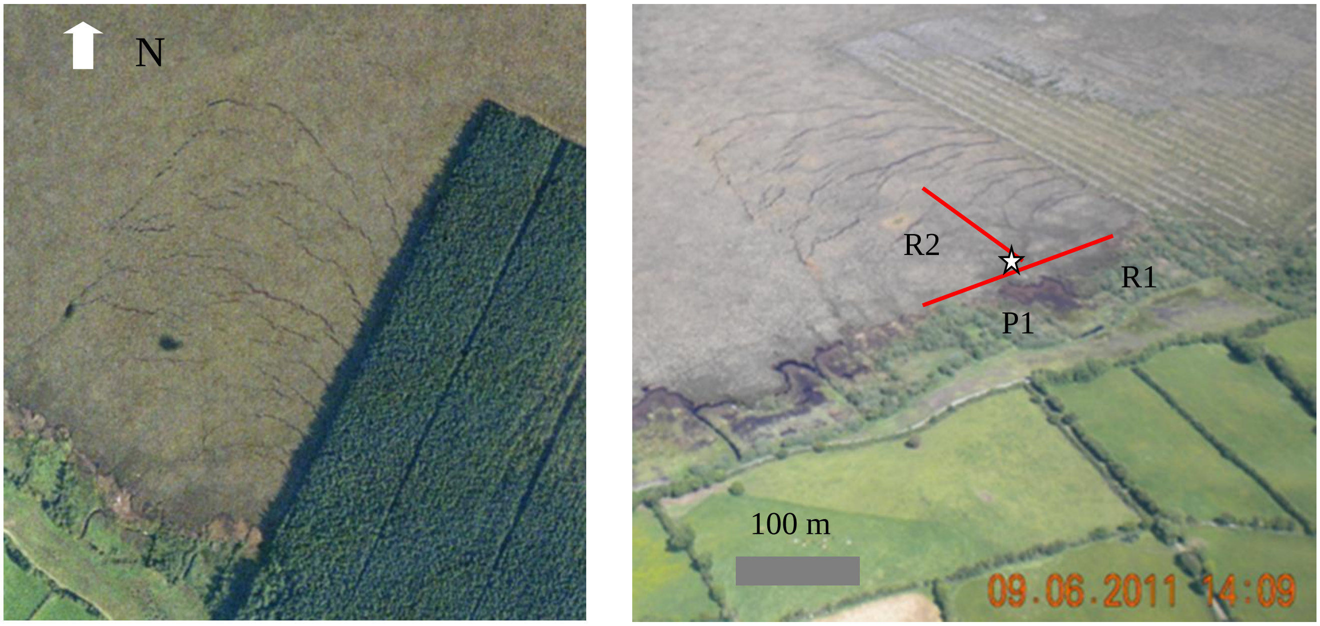


Figure 3. Southern failed area at Carn Park bog (a) from 2005 aerial photograph (courtesy Charise Mc Keown - Geological Survey of Ireland) and (b) Section of 2011 ortho rectified photograph of Carn Park bog (courtesy Andrea Webb, National Parks and Wildlife Services). R1 and R2 represent the ERT profiles and P1 the deep peat probe

Figure 4. Photographs of southern failed area of Carn Park bog (a) new pool in south-west corner of failed area thought to be origin of the failure (photo from Dec 2006) and (b) photograph of crack from February 2011

Figure 5. Section of Aghnamona Bog, Roosky (a) 2005 aerial photograph pre-failure (courtesy Charise Mc Keown - Geological Survey of Ireland) and (b) image from Google Maps 2011 (www.google.com)

Figure 6. Photographs of cracking on Aghnamona bog, Roosky (April, 2011)

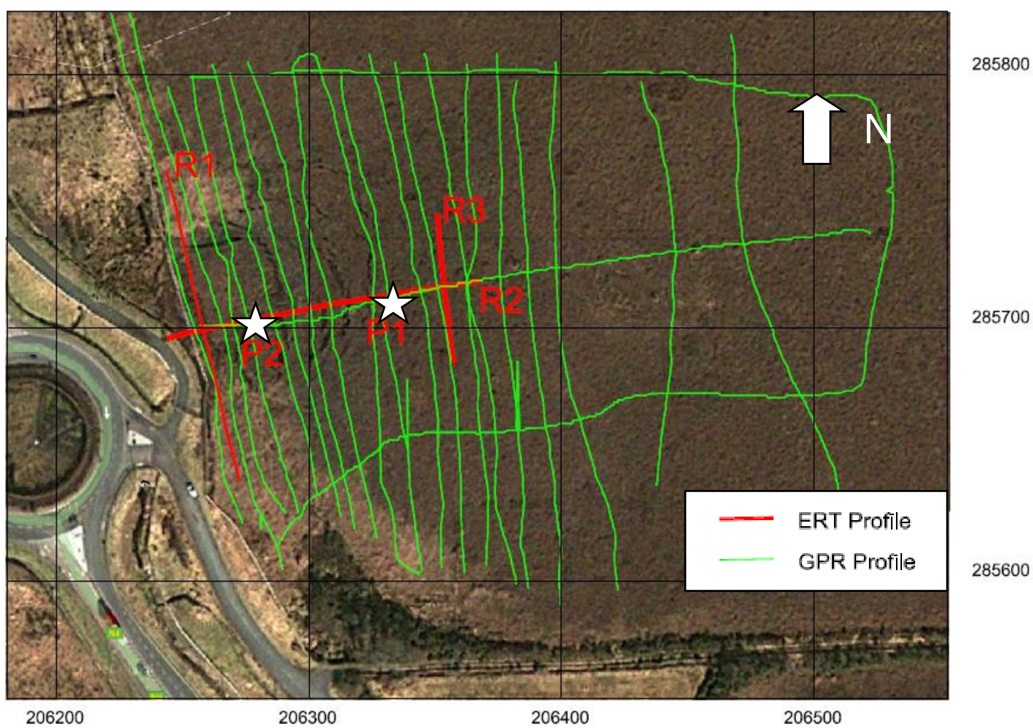


Figure 7. Test locations at Roosky site (east and north co-ordinates are given in m). Location of ERT test lines and deep probes are designated R1, R2 and R3 and P1 and P2 respectively.

Figure 8. Man-hauling 100 MHz GPR antenna at Roosky

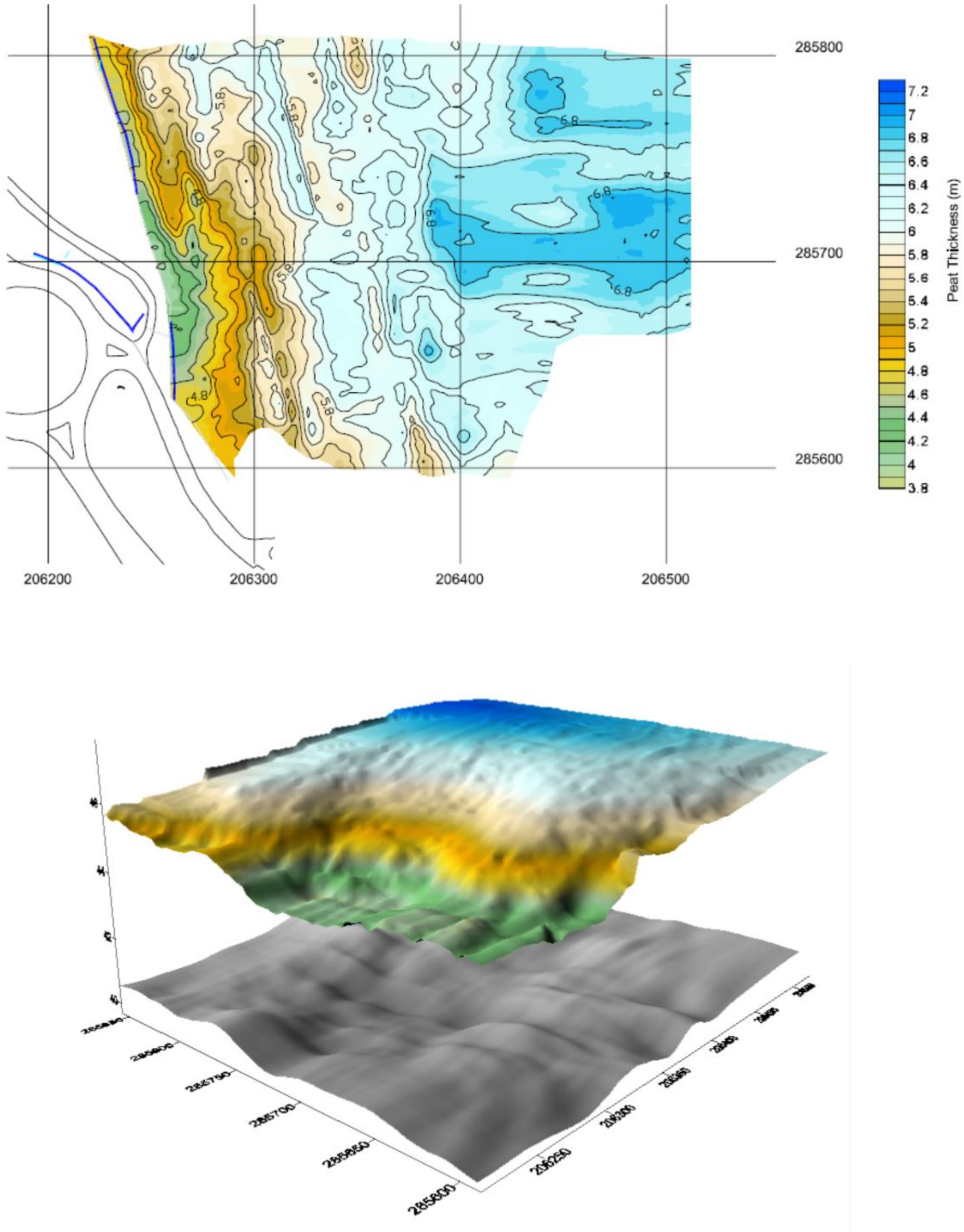


Figure 9. (a) peat thickness and (b) 3D plot of surface and peat base topography for Aghnamona bog, Roosky. (East and north co-ordinates and elevation are given in m).

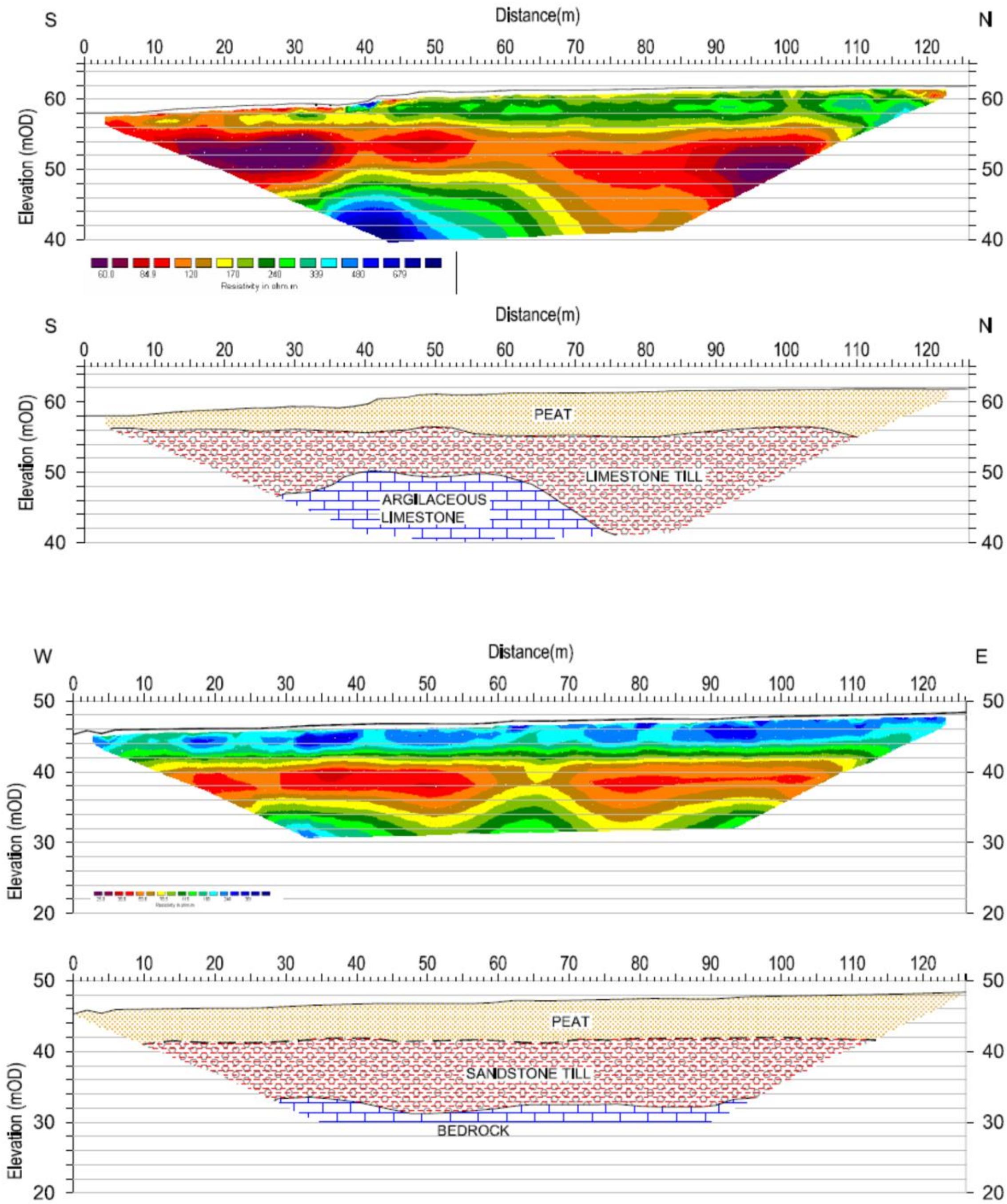


Figure 10. ERT profiles through the failed areas (a) Carn Park – Profile R2 and (b) Roosky - Profile R2. See Figures 3b and 7 for locations.

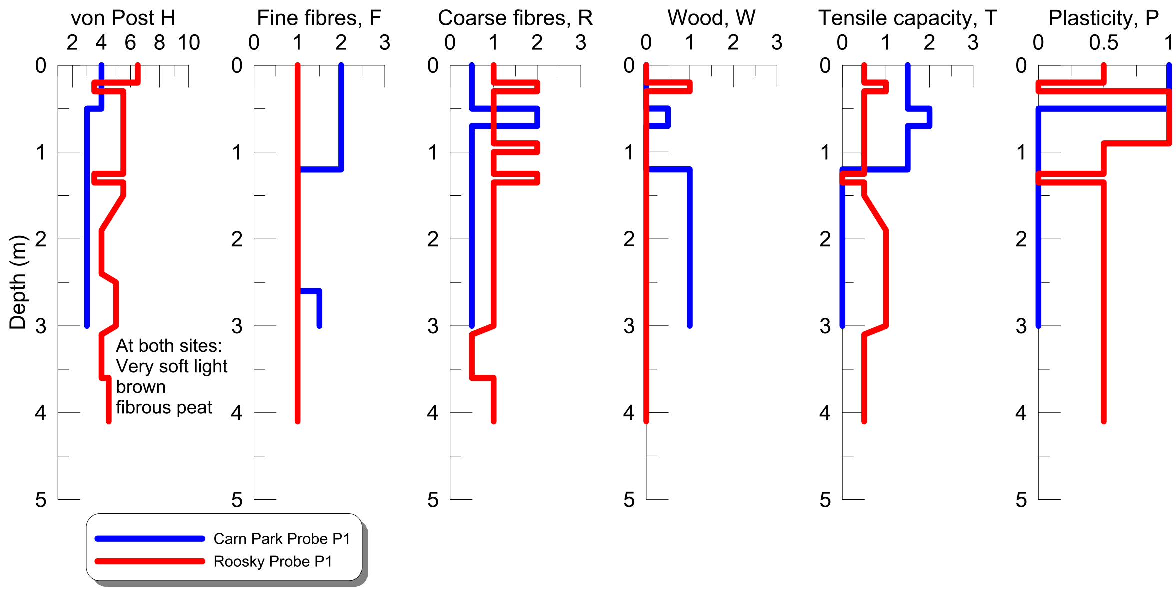


Figure 11. von Post and Granlund (1926) peat logs
(H = degree of humification: 1-10, F = fine fibres: 0-3, R = coarse fibres: 0-3, W = wood: 0-3, T = tensile strength: 0-3, P = plastic: 0 or 1)

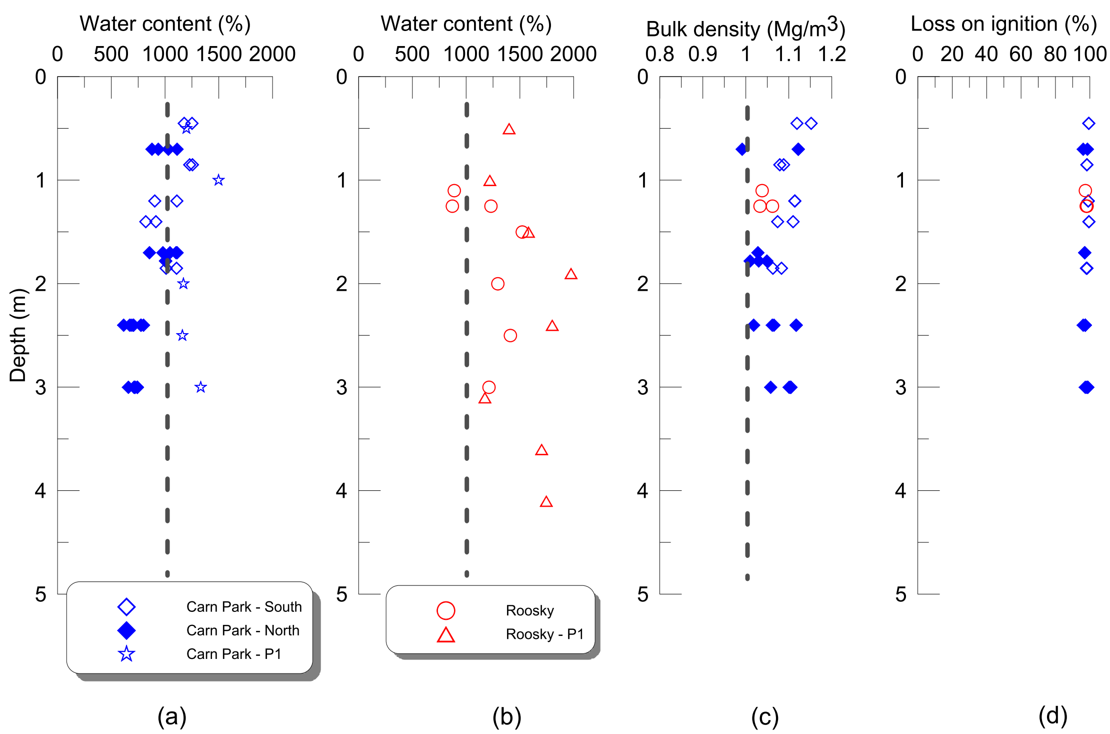
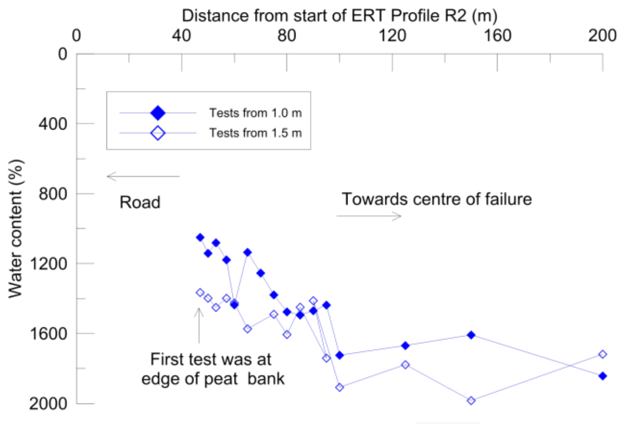
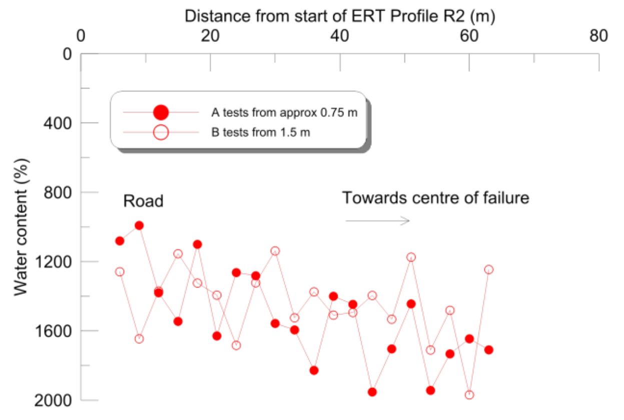


Figure 12. Basic characteristics of Carn Park and Roosky peat (a) Carn Park water content, (b) Roosky water content, (c) bulk density both sites and (c) loss on ignition at 440°C both sites



(a)



(b)

Figure 13. Longitudinal profiles of water content (a) Carn Park and (b) Roosky

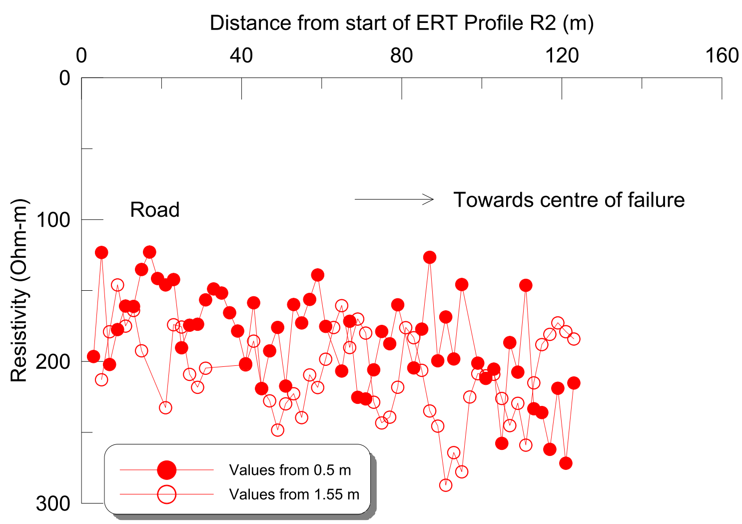


Figure 14. Longitudinal profile of resistivity for Roosky site

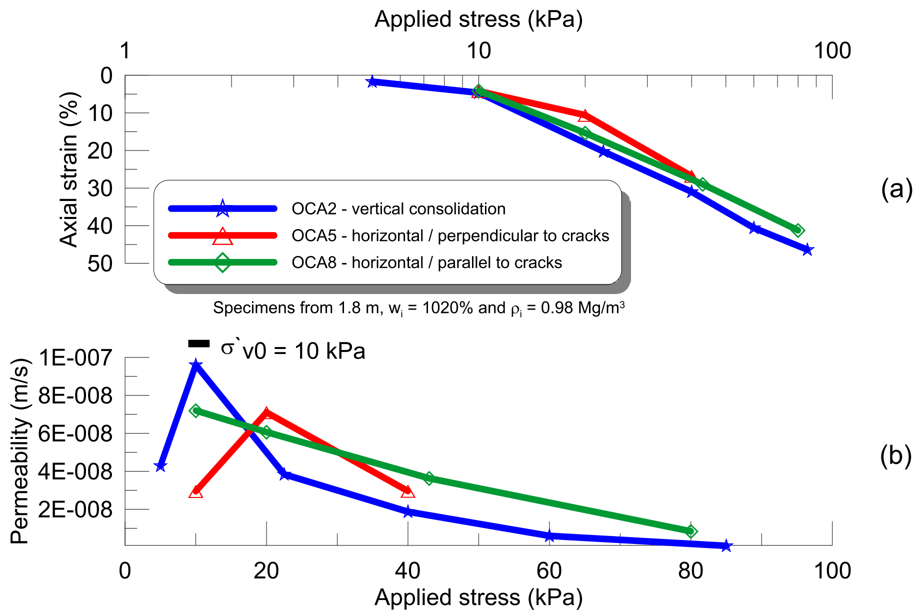


Figure 15. Summary of oedometer tests from Carn Park southern area at 1.8 m (a) stress versus strain and (b) permeability versus strain

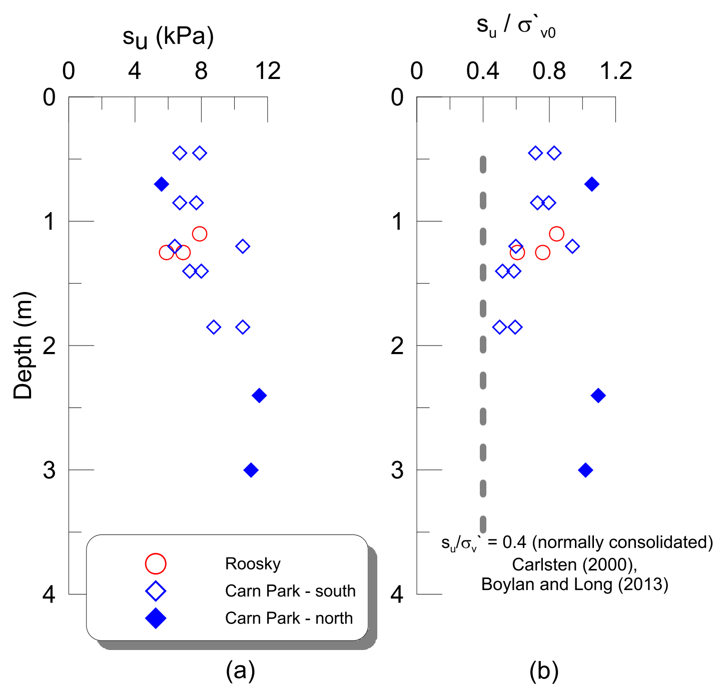


Figure 16. Undrained shear strength from DSS tests (a) s_u versus depth and (b) s_u/σ_{v0}' with depth